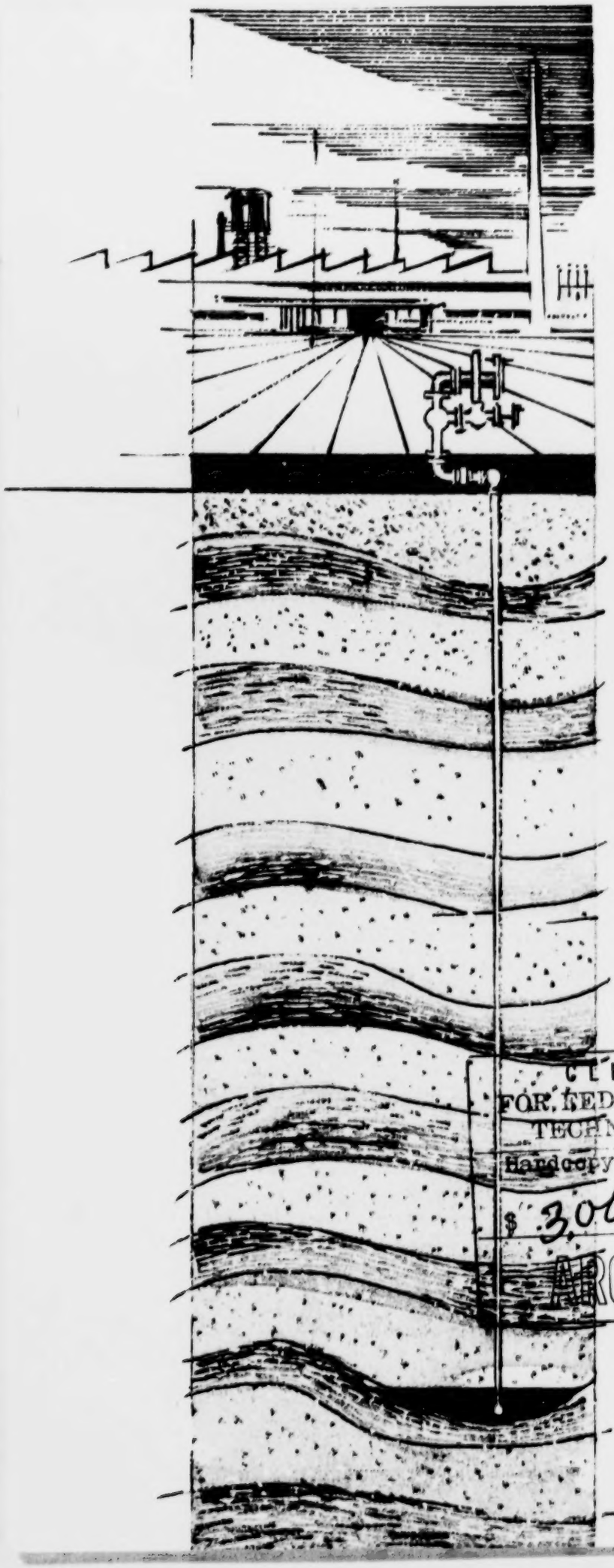

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ENVIRONMENTAL HEALTH SERIES
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DEEP-WELL INJECTION OF LIQUID WASTE

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ERRATA

Page 2, Paragraph 3
Louisiana should be listed among the states with several injection wells.

Page 2, Paragraph 6
The cost of existing wells is discussed on page 32.

Page 15, Paragraph 1
A method of testing injection wells to establish their critical input pressures is described on page 18.

Page 49, Reference 81
V. 7

DEEP-WELL INJECTION OF LIQUID WASTE

A Review of Existing Knowledge and an Evaluation of Research Needs

by

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Basic and Applied Sciences Branch
Robert A. Taft Sanitary Engineering Center

U. S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
Public Health Service
Division of Water Supply and Pollution Control
Cincinnati, Ohio

April 1965

The ENVIRONMENTAL HEALTH SERIES of reports was established to report the results of scientific and engineering studies of man's environment: The community, whether urban, suburban, or rural, where he lives, works, and plays; the air, water, and earth he uses and re-uses; and the wastes he produces and must dispose of in a way that preserves these natural resources. This SERIES of reports provides for professional users a central source of information on the intramural research activities of Divisions and Centers within the Public Health Service, and on their cooperative activities with State and local agencies, research institutions, and industrial organizations. The general subject area of each report is indicated by the two letters that appear in the publication number; the indicators are

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FOREWORD

Direct use of the soil and subsurface formations for treating, containing, disposing, or reclaiming water from liquid wastes is a relatively untapped means of water pollution control. Soil utilization offers advantages as an alternative to more conventional methods of handling wastes and may eliminate the need for waste disposal to surface waters in many instances. To be practicable, land-waste disposal methods must also be handled in such a manner as to protect ground water quality. One of the objectives of the Engineering Research Section of the Water Pollution Control Division is to develop the background of scientific and engineering knowledge to permit formulation of reliable design and operating criteria for techniques of using surface soils and subsurface formations for water pollution control.

This report on deep-well injection is one of a series of reviews of the status of knowledge and research needs concerning one technique of land disposal. Subsequent reports will cover other techniques.

Gordon G. Robeck
Chief, Engineering Section
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ABSTRACT

A review of the knowledge pertinent to the use of deep wells for the subsurface injection of liquid waste has been carried out to evaluate the technical and economic feasibility and desirability of this method and to outline existing research needs.

This review has shown that the deep-well injection of liquid waste is technically feasible in many areas of the country and, if properly planned and implemented, is not likely to be harmful to natural resources.

While most of the technical knowledge and experience necessary to carry out the deep-well injection of liquid waste is presently available, further investigation is necessary to solve specific problems that remain as barriers to the safe, efficient, and economic use of this method.

DEEP-WELL INJECTION OF LIQUID WASTE

INTRODUCTION

The purpose of this report is to evaluate existing knowledge pertinent to the use of deep wells* for the subsurface injection of liquid waste and to outline the research needed to allow interested agencies and individuals to estimate more easily the technical and economic feasibility and desirability of this method.

Numerous studies, many of them cited here, have been done with regard to the feasibility of using deep wells for the subsurface injection of radioactive waste. No comprehensive study has, however, been made to evaluate the use of deep wells for injection of toxic liquid wastes other than radioactive ones.

Highly toxic, nonradioactive wastes are produced by various industries, for example, metal-plating and chemical industries, in many areas of the country. These wastes may be virulent, relatively indestructible contaminants if discharged into usable waters. Wastes containing these contaminants can be concentrated, but the problem of ultimate disposal remains.

Stephan *(1)* has listed several processes by which permanent disposal of concentrated, unusable, inorganic wastes can be accomplished. These processes are, in the order of increasing cost: Spreading on the surface of the earth, deep-well injection, placement in cavities, wet oxidation, and incineration. Priesing *(2)* has listed other possible methods of ultimate disposal: Biochemical oxidation, radiation decomposition, and use for biological fuel cells.

Deep-well injection is not actually a disposal method, but rather a storage method, since wastes injected into an underground stratum remain there indefinitely if the injection program is properly planned and carried out. A question of major importance is, therefore, under what conditions should this storage space be used for liquid waste? This report does not attempt to answer that question but only to examine the more obvious factors involved in making such a decision. In addition, some of the technical methods and tools available for the construction, evaluation, and operation of injection wells are considered.

EXISTING WELLS

Deep wells are used in oil-producing states for underground disposal of the saline water brought to the surface with the oil. The importance of this procedure to the preservation of surface- and ground-water quality in these states is clear when it is realized that, in the United States, 6 billion barrels of saline water was removed from the ground through oil wells in 1956 *(3)*.

*Deep wells, as discussed in this report, may range from a few hundred feet to over 12,000 feet in depth. Well depth at any specific location depends on the depth required to reach a porous, permeable, salt-water-bearing stratum that is confined vertically by relatively impermeable beds.

The total number of brine injection wells in the United States is not known. Kansas *(4)* has issued permits for about 3,000 of these wells, which has been stated to be more than exist in all the other states combined *(5)*.

The number and location of deep wells for injection of wastes other than oilfield waters is not accurately known, since no comprehensive, authoritative survey of registered existing wells has been made, and no means has been established for the permitting and registering of these wells in some states.

Talbot and Beardon *(6)* found that a total of at least 50 industrial-waste injection wells exist in the States of California, Colorado, Indiana, Iowa, Kansas, Louisiana, Michigan, New Mexico, Oklahoma, Pennsylvania, Tennessee, and Texas. By correspondence with state agencies and by examination of the literature, the writer has determined that a total of about 50 deep industrial-waste injection wells exist in the States of Michigan, Texas, and California alone. Oklahoma and Kansas have injection wells, but their number is not known. Colorado, Florida, Indiana, Iowa, New Mexico, and Pennsylvania have one or two wells each. Alaska, Missouri, New York, Washington, and West Virginia have reported having injection wells, but that these are deep wells, as defined earlier, or that they are for industrial-waste injection is not certain. Deep industrial-waste injection wells have been constructed in the Canadian Provinces of Ontario and Alberta.

Some articles that describe specific individual wells have been published by Adinoff *(7)*, Cecil *(8)*, Henkel *(10,11)*, Holland and Clark *(12)*, Hundley and Matulis *(13,14)*, Lansing and Hewett *(15)*, Lee *(16)*, MacLeod *(17)*, Mechem and Garrett *(18)*, Paradiso *(19)*, Sadow *(20)*, Scopel *(21)*, Moffett *(46)*, Batz *(145)*, and Graves *(146)*.

The above-cited articles, information from the "Inventory of Municipal and Industrial Waste Facilities" *(22)*, and written communications from the individual states indicate that deep wells have been used to inject spent sulfuric acid, spent caustic, cooling tower and boiler water, and phenolic wastes from petroleum refineries; caustic wastes, phenolic wastes, and concentrated brines from petrochemical plants; spent brines from chemical plants using brine as a chemical source; produced wastes from a natural gas purification and compressor plant; miscellaneous chemicals from chemical- and pharmaceutical-product plants; spent pulping liquors from a paper mill; radioactive uranium mill wastes; phenols and quench water from a coking plant; unidentified wastes from two food product plants; and unidentified wastes from several metal-product plants.

The majority of reported industrial-waste injection wells range in depth from a few hundred to 6,000 feet, one well exceeding 12,000 feet *(18,21)*. Existing wells are injecting waste into sandstones and limestones with the exception of one well *(18,21)*, which is injecting into fractured gneiss. The cost of existing wells is discussed on page

SITE SELECTION

General Geologic Considerations

Rocks that comprise the earth's crust are classified as igneous, metamorphic, and sedimentary. Although all these rocks can, under the proper circumstances, have sufficient porosity and permeability to act as reservoirs for injected fluids, consolidated sedimentary rocks are most likely to have the geologic characteristics suitable for waste injection wells. These characteristics are:

1. The injection horizon should have sufficient porosity, permeability, and areal extent to act as a liquid storage reservoir at safe injection pressures.
2. The injection horizon should be vertically below the level of fresh water and should be separated vertically from fresh water and other natural resources by rocks that are, for practical purposes, impermeable to waste.

Most sedimentary rocks with these characteristics were deposited in a marine environment and, below the present level of fresh-water circulation, contain saline water in the pores. This interstitial saline water is not suitable for most purposes and only occasionally contains enough dissolved minerals to be commercially valuable. These sedimentary rocks do, however, contain naturally occurring oil, gas, coal, and sulfur, and in some localities, sedimentary strata are used as storage reservoirs for natural gas. Important considerations in selecting a waste injection well site are, therefore, the protection of developed and undeveloped deposits of minerals and hydrocarbons, and the preservation of possible gas storage reservoirs.

Sedimentary rocks porous and permeable enough in the unfractured state to accept relatively large volumes of waste are sandstones, limestones, and dolomites. Naturally fractured limestones and shales may provide satisfactory injection horizons, since oil and gas are produced from these rocks in many areas *(23)*. Artificially fractured shales have been suggested as reservoirs for liquid radioactive waste *(24)*.

Confining strata that are, for practical purposes, impermeable must overlie and underlie the injection horizon to prevent the vertical escape of injected waste. Unfractured shale, clay, salt, anhydrite, gypsum, marl, and bentonite have been found to make good seals against the upward flow of oil and gas *(25)*. Limestone or dolomite might provide a satisfactory seal, but since these rocks often contain open fractures or solution channels, their adequacy as confining beds would have to be carefully evaluated in each case. The necessary thickness for a confining stratum cannot be rigidly specified; however,

Russell *(25)* has stated that the minimum thickness of a good seal to retain oil may be only 10 to 20 feet. In many cases, hundreds or thousands of feet of relatively impermeable strata may enclose a possible injection horizon and virtually insure its segregation. If insuring that injected waste is confined laterally as well as vertically within a selected horizon is desired, waste can be injected into localized geologic structures.

Sedimentary rocks have commonly been uplifted, folded, and faulted by forces in the earth's crust after their original deposition in relatively uniform layers at the bottom of ancient seas. The folds are positive ones (anticlines) and negative ones (synclines). Faults offset strata and place them in contact with other older or younger beds of the same or different rock types. Oil and gas often occur in anticlinal folds since these fluids are less dense than water and seek a position of lowest fluid potential. Anticlinal structures are used for gas storage reservoirs for this same reason. Injected waste with a density less than that of interstitial water would tend, therefore, to remain trapped in closed anticlinal structures whereas waste with a density greater than that of interstitial water would tend to remain trapped in closed synclinal structures.

Injecting wastes of relatively high specific gravity into closed synclines seems advisable, wherever possible, since they could not then leak upward into fresh-water-bearing strata and could not migrate laterally into hydrocarbon-bearing geologic structures (anticlines). This procedure has been suggested by others *(26)*.

Porous and permeable sandstone bodies entirely surrounded by impermeable shales exist in many areas of the United States and have been suggested as possible reservoirs for liquid radioactive waste *(27)*. These sands are restricted in thickness and areal distribution *(28)*, and, while the total amount of waste that can be injected at safe pressures would be restricted, the injected waste would presumably be contained within a well-defined reservoir. Other types of structural and stratigraphic traps contain oil and gas *(23)* and would also hold injected waste under the proper conditions.

In aquifers where a hydrodynamic gradient exists, the mechanics of fluid entrapment are modified; these conditions have been discussed by Hubbert *(29)*. This factor should be considered in selecting a waste injection well site where lateral confinement of the waste is desired.

Areas Geologically Suitable for Deep-Well Injection

The specific location of a waste injection well site must be determined from a detailed analysis of local geology. Generalizations can, however, be made, based on regional geologic considerations, concerning the suitability of some areas for waste injection wells.

Synclinal basins, such as those shown in Figure 1,* are of particular interest in the consideration of injection well sites because they contain relatively thick sequences of salt-water-bearing sedimentary rocks and because the subsurface geology of these basins is often well known as a result of wells' having been drilled for oil and gas. In addition, if these basins are closed ones, fluids are believed to be unable to circulate out of them.

Because of their comparatively favorable geologic characteristics, synclinal basins have received consideration as sites for the injection of liquid radioactive waste. Repenning *(30,31)* has reported on the San Juan basin and the Central Valley of California, Colton *(32)* on the Appalachian basin, deWitt *(33)* on the Michigan basin, Sandberg *(34)* on the Williston basin, and Beikman *(35)* on the Powder River Basin. LeGrand *(36)* has reported on the Atlantic and Gulf Coastal Plains. Other basins (Figure 1) are under study by members of the United States Geological Survey and by the Subcommittee on Atomic Waste Disposal of the American Association of Petroleum Geologists.

Many of the findings of the above-cited studies are applicable to the injection of fluids other than radioactive waste. Since, however, the deep-well injection of radioactive waste may involve problems (such as heat generation and extreme toxicity) not encountered in the injection of other fluids, the conclusions do not all apply to the present study. Data concerning some of the basins of greatest interest for industrial-waste injection are summarized in the following paragraphs.

The Central Valley of California *(31)* is about 450 miles long and has an average width of about 40 miles (Figure 1). As much as 50,000 feet of sedimentary rocks accumulated in the northern part of the Central Valley and 25,000 feet in the southern part. Sandstones that would provide suitable injection horizons are present in this thick sequence of sedimentary rocks, but several factors intrude on their use for waste injection. These are:

1. Rapid lateral changes in rock properties, which make the evaluation of possible injection horizons difficult;
2. the danger of seismic activity, which could rupture casing in the injection wells or in nearby abandoned wells or perhaps damage the confining strata;
3. the presence of extensive oil and gas accumulations;
4. the general extension of potable ground water to depths of 2,000 to 3,000 feet.

*With the exception of the Appalachian basin and the Central Valley of California, only the approximate extent of the closed portions of the various basins are shown in Figure 1.

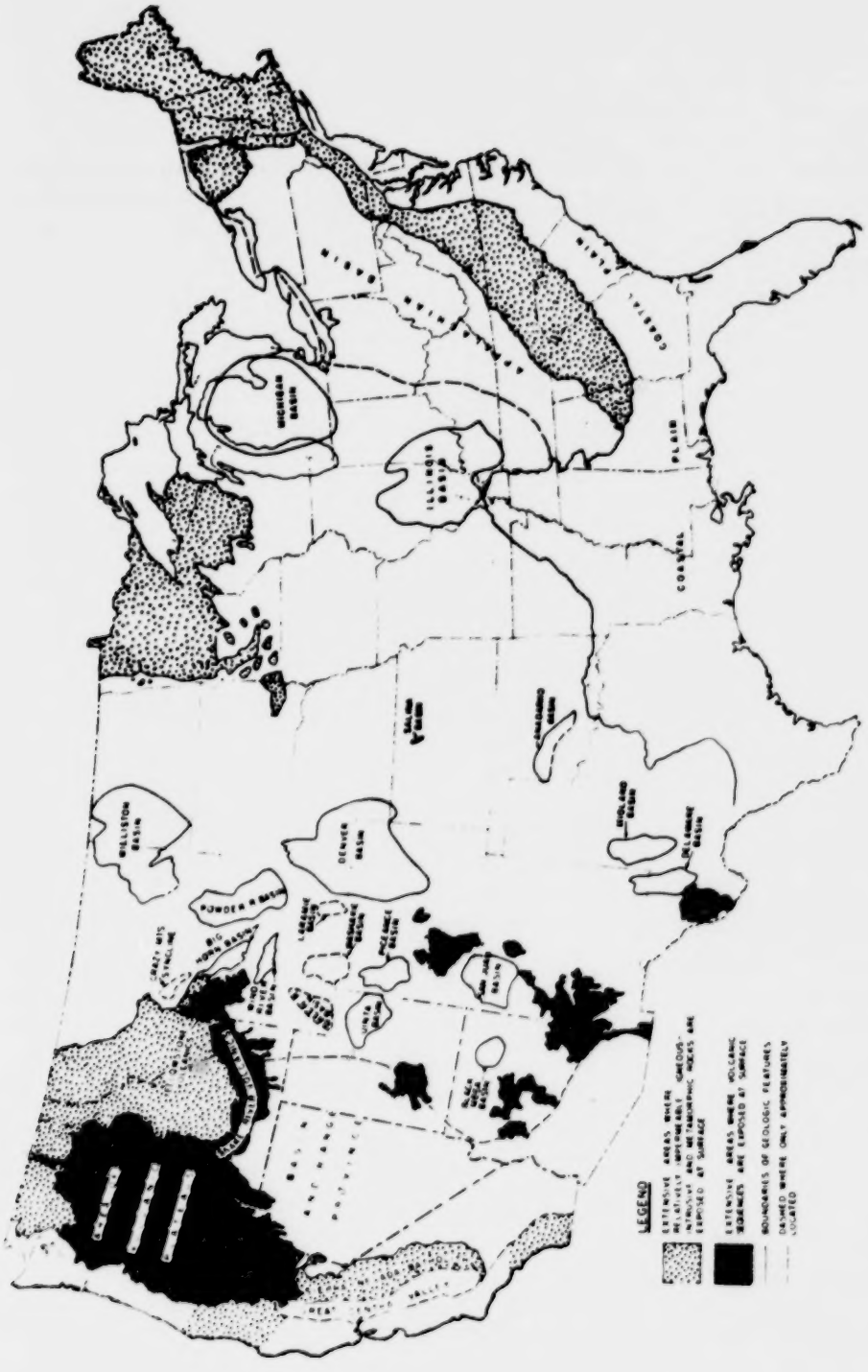

Figure 1. Geologic features significant in evaluation of well sites for deep waste injection. Data obtained from tectonic map of the United States, American Association of Petroleum Geologists, 1944.

The Appalachian basin *(32)* is not a clearly defined closed basin, as are some of the other basins shown in Figure 1, but is a broad structural downwarp that contains relatively thick sequences of sedimentary rocks. Within the Appalachian basin, many smaller geologic structures exist, and each would have to be considered individually for its suitability as a waste injection site; however, Colton *(32)* has outlined broad areas of the Appalachian basin with regard to their suitability for radioactive waste disposal. The areas he considers generally unsuitable are underlain by complexly folded and faulted Paleozoic rocks, have sedimentary sequences less than 2,000 feet thick, or are underlain by rocks containing comparatively large volumes of coal, oil, or gas. These factors also limit the suitability of the outlined areas for the injection of liquid wastes other than radioactive ones.

The Michigan basin, as outlined by deWitt *(33)*, covers about 122,000 square miles in parts of five states and the Province of Ontario. At the central part of the basin, sedimentary rocks are more than 14,000 feet thick. Sandstones and limestones are present that are suitable for waste injection, but injection should be carefully controlled, since these rocks contain ground water to depths of greater than 1,000 feet and also contain commercially valuable brines and hydrocarbons.

The Atlantic and Gulf Coastal Plains *(36)* (Figure 1) are not basins, but Tertiary, Cretaceous, and older sediments, which comprise all but the most superficial covering and dip generally toward the sea. These sediments are generally at least several thousand feet thick. The uppermost few hundred feet of these seaward-dipping sediments may contain fresh water, but at depths greater than this, the water is saline.

Several factors tend to make some parts of the Coastal Plain less suitable for injection well sites than others. The Texas and Louisiana Gulf Coast is less favorable because of the immense oil- and gas-bearing potential of the sedimentary strata and because of the relatively high fluid pressures found in the subsurface in some areas. Much of peninsular Florida may not be suitable for injection wells, because of the importance of ground water and because of uncertainty that the deeper rocks are adequately sealed from the shallower fresh-water-bearing ones.

Just as major synclinal basins are generally geologically favorable sites for deep-well injection, other areas may be unfavorable because they have a relatively thin sedimentary rock cover or none at all. Extensive areas where relatively impermeable igneous-instrusive and metamorphic rocks are exposed at the surface are shown in Figure 1. These regions can generally be eliminated from consideration as possible waste injection well sites. In addition to the areas shown in

Figure 1, in much of the Rocky Mountain region, between the numerous intermountain basins, crystalline rocks are exposed at the surface or lie near the surface. Igneous-intrusive and metamorphic rocks lie at or near the surface in much of the region north of the Columbia River-Snake River-Yellowstone volcanic area (Figure 1).

Regions wherein a thick volcanic sequence lies at the surface (Figure 1) are not generally suitable for waste disposal wells. Although volcanic rocks have fissures, fractures, and interbedded gravels that will accept injected fluids, they contain fresh water.

The immense and geologically complex Basin and Range Province (Figure 1) is a series of narrow basins and intervening structurally positive ranges. Some of the basins might provide waste injection sites, but their geology is largely unknown and the cost of obtaining sufficient information to allow the safe construction of injection wells would be very great.

The geology of the West Coast is complex and not well known. Relatively small Tertiary sedimentary basins in southern California produce large quantities of oil and gas, and would be generally geologically satisfactory sites for waste injection wells. These basins exist along the coast of northern California, Oregon, and Washington, but their geology is poorly known.

Large areas of the Midwest and West have not been discussed since they are not underlain by major basins or by prominent geologic features that characterize other regions. These areas may be generally satisfactory for waste injection if they are underlain by a sufficient thickness of strata that contain saline water and if potential injection horizons are sealed from fresh-water-bearing strata by impermeable confining beds.

DRILLING, EVALUATION, AND COMPLETION OF INJECTION WELLS

Drilling Injection Wells

The type of equipment used for drilling an injection well can influence the well's economics and performance. Oil and gas wells are drilled primarily with rotary drills, and this type of equipment is, therefore, most readily available. Cable-tool drills are, however, still used by the oil industry and may, under certain conditions, be more desirable than rotary drills. The following paragraphs con-

cerning disposal well drilling have been extracted from the American Petroleum Institute's publication "Subsurface Salt-Water Disposal" *(37)*.

"Drilling the well down to the disposal formation is carried on in accordance with accepted practices within the area. The only drilling of the disposal well which will be discussed is the actual drilling of the disposal formation.

"Cable tools are frequently used for drilling the disposal formation, particularly where casing is set above the formation. There are many areas, however, where the use of cable tools is not feasible because of high pressure, extreme depths, soft formations, etc., as in the Gulf Coast region.

"The chances for formation damage are less when drilling with cable tools than with rotary tools. Mud and lost-circulation material will not be lost to the formation, which could cause a plugging action. Drilling is at a slower rate with cable tools, but in most areas their cheaper price rate offsets the difference in drilling rates.

"When rotary tools are used to drill the disposal formation, there are several procedures which can be followed. The well or formation conditions and accepted or proved practices within an area help determine which will be used. These practices are:

"1. Drill full-sized hole to total depth and set casing through porous disposal zone or zones. This method is recommended for unconsolidated formations subject to sloughing or caving.

"2. Drill a full-sized hole through all porous zones or to where circulation is lost and set casing immediately above the porous disposal zones.

"3. Drill a full-sized hole to immediately above, or to the top of, the disposal formation and set casing at this point. Then, drill a reduced-sized hole through all the porous zones or until circulation is lost.

"If possible, clear water should be used for drilling fluid in drilling the reduced hole, to prevent plugging from mud and lost-circulation material.

"4. Drill a full-sized hole to immediately above, or to the top of, the disposal zone, then drill a reduced-size (rat hole) to total depth and set casing at the point where the hole size was reduced. After casing has been

set, ream the reduced hole to remove mud or invaded zone, using water for the drilling fluid.

"If casing and hole size permit, the rat-hole may be reamed with a larger-diameter bit in a conventional manner. If conventional reaming cannot be done, the rat-hole may be underreamed."

Koenig *(38)* attempted to determine the cost of drilling holes of various sizes and found that, in oil-well drilling, hole diameter does not enter as a strong determinant in considering well-drilling cost, but that the trend is to smaller size hole and casing to reduce overall costs. He also determined that, for 98 typical drilling programs in the United States, the median diameter of the production hole was 8¾ inches.

Evaluation of the Injection Horizon

The physical characteristics of the subsurface horizon into which waste liquids are to be injected can be evaluated by means of various geologic and engineering techniques and tools. Some of the rock properties can be estimated from samples taken from surface outcrops, if such outcrops exist. More reliable information can be obtained from the records of nearby deep wells, from samples taken from the injection well, and from tests run in the well during and after drilling.

Information obtainable from surface outcrops includes porosity, permeability, and mineralogy of rock specimens, and the thickness and sequence of strata. The same information can be obtained from subsurface rock samples taken during drilling and from various types of well-logging devices. In addition, evaluation of the gross physical properties of the injection horizon, such as fluid pressure, temperature, and flow rate, can be measured. The permeability (transmissibility), storage coefficient, critical injection pressure, and injectivity index of the injection horizon can be measured by pumping tests and injection tests. Samples of reservoir fluid can be obtained in small quantities from subsurface rock samples or in larger quantities from flowing or pumping of the disposal horizon.

Knowledge that should be obtained for any injection well is: Depth to which fresh water extends; sequence of geologic formations; thickness, porosity, permeability, and temperature of the injection horizon; and quality of water and fluid pressure in the injection horizon. Much of this information must be obtained before a well is cased. Cores should be taken at the injection horizon to allow direct evaluation of porosity and permeability, and determination of possible reactions

between the rock and the waste product. These cores can be taken during drilling or as sidewall cores before the hole is cased.

Pumping or injection tests are commonly employed in ground-water basin and oilfield development to determine the capability of the aquifer or reservoir rock to produce or accept water or hydrocarbons.

SUBSURFACE EVALUATION METHODS

Subsurface-formation evaluation methods can be classified according to whether they are used while drilling is in progress or after the hole or a portion of it has been drilled. Drill cuttings and cores are obtained during drilling. Electric logs, sonic logs, radioactive logs, and drill stem tests can be run after the entire hole or a portion of it has been drilled. Pumping and injectivity tests can be performed through the drill stem before the hole has been completed, or through the casing or tubing after the hole has been completed.

Table 1 summarizes the information that might be desired in evaluating an injection horizon in the subsurface, and the methods available for obtaining it. (see References 39,40, and 41 for a complete discussion of evaluation methods and tools).

Table 1. SUMMARY OF INFORMATION DESIRED IN SUBSURFACE EVALUATION OF DISPOSAL HORIZON, AND METHODS AVAILABLE FOR EVALUATION

Information desired	Methods available for evaluation
Porosity	Cores, electric logs, radioactive logs, sonic logs
Permeability	Cores, pumping or injection tests, electric logs
Fluid pressure in formations	Drill stem tests
Water samples	Cores, drill-stem tests
Geologic formations intersected by hole	Drill time logs, drilling samples, cores, electric logs, sonic logs, radioactive logs, caliper logs
Thickness and character of disposal horizon	Same as above
Mineral content of formation	Drilling samples, cores
Temperature of formation	Temperature log
Amount of flow into various horizons	Injectivity profile

Some of the logging tools listed in Table 1 can be rented or purchased and used by the well owner, but the usual practice is to have the work performed by contract with an oilfield service company specializing in this work.

Core Analysis

As has been mentioned, some of the rock properties that can be determined by core analysis are porosity, permeability, and mineralogy. The fluids in the core can also be removed and analyzed. Recommended practices for core handling and analysis (RP40) and permeability determination (RP27) have been published by the American Petroleum Institute *(42,43)*. These publications and those by Rall and others *(44)* and Champlin *(45)* contain abundant references to porosity and permeability determination. Core analyses can be performed by companies specializing in this work. In using porosity and permeability data from core analyses, a single core sample may not be representative of the injection horizon as a whole. Levorsen *(23)* has shown that permeability determinations from a single oil pool can vary by several hundredfold or thousandfold.

The type of fluid used in core analyses can influence the value of the coefficient of permeability, especially when clay minerals are present *(43)*. This factor could be particularly important in liquid-waste injection where changes in permeability of a rock could be caused by the injection of chemical solutions greatly different from the fluids used for conventional laboratory permeability determinations.

Short-Term and Ultimate Capacity of a Well

Factors restricting injection rate and ultimate injection capacity. Experience with injection wells indicates that wide variation in input rate can exist. Moffett *(46)* has stated that one well for injecting waste water from a chemical plant into porous sandstone accepted water at rates as high as 600 gallons per minute (gpm) at a wellhead pressure of 210 pounds per square inch (psi). On the other hand, Cecil *(8)* has reported that the initial intake rate of a disposal well in Texas (in a sandstone of low permeability) was only 31 gpm at an injection pressure of 500 psi. Oilfield experience shows that intake rates could be greater or less than these.

The intake rate of an injection horizon at any limiting pressure is controlled by the permeability (transmissibility) of the horizon. Talbot and Beardon *(6)* found that the most frequent flow rate in industrial-waste injection wells is in the range of 100 to 300 gpm.

It can be shown that vast amounts of pore volume exist in buried strata. According to Weeks *(48)*, it has been estimated that the ultimately recoverable oil reserves in the United States may reach 2,000 billion barrels (84 trillion gallons). This oil occupies only a small fraction of the actual available space. For further comparison, in 1956, according to one estimate *(3)*, 6 billion barrels (252 billion gallons)

of salt water was removed from the ground through oil wells in the United States.

Each cubic foot of rock, with a porosity of 20 percent, can contain about 1 ½ gallons of waste. The storage volume available to a well in an underground reservoir can be computed to be (by ignoring the effect of the well bore):

$$V = 7.481 \pi r^2 h \phi = 23.505 \ r^2 h \phi \text{ gal} \quad (1)$$

where:

r = radius of available storage area, ft
h = thickness of reservoir stratum, ft
ϕ = porosity.

A reservoir 50 feet thick with a porosity of 0.20 could contain about 2.1 billion gallons of waste per square mile or 590,000 gallons of waste within 50 feet of the well and 410 million gallons within ¼ mile of the well. Available pore volume could control the ultimate storage capacity of an injection horizon if waste were injected into a depleted gas reservoir, as has been contemplated by Crawford *(49)* and Wainerdi *(50)*, or if the areal boundaries of the injection horizon were restricted by law or by the presence of other wells in the injection horizon. If the areal boundaries of the injection horizon are restricted, the rate of longitudinal dispersion of the moving fluid front could be important. Dispersion occurs in homogeneous media *(51)* but could be particularly serious in fractured or cavernous strata where a plume of waste could flow through a permeable channel far ahead of the main body of injected liquid.

In most cases, the ultimate storage capacity of an injection well is probably controlled by the rate at which injection pressure increases at the desired injection rate. Injection pressure is a limiting factor because:

1. Excessive pressures cause hydraulic fracturing and consequent possible damage to confining strata *(52-54)*.
2. The pressure capacity of injection well pumps, tubing, and casing is limited.
3. In some states, maximum injection pressures are specified by regulatory agencies.

Although it is unlikely that hydraulic fracturing results in damage to confining beds *(55)*, it would seem prudent to consider the pressure at which hydraulic fracturing occurs as being the maximum safe injection pressure until this question is resolved, particularly in cases where confining strata are relatively thin and vertical confinement is essential.

Hubbert and Willis *(52)* concluded that the hydraulic pressure required to cause fracturing depends on the magnitude of regional rock stresses, hole geometry, the character of the rock strata (presence of flaws, etc.), and the penetrating quality of the fracturing fluid.

Theoretical considerations *(52,56-58)* lead to the prediction that fractures will be formed in a plane perpendicular to the least regional principal stress if other factors, such as pre-existing rock flaws, do not interfere. In areas where active tectonic compression exists (California, for example), the plane of least stress may be vertical. If so, the fractures would be horizontal and the pressures necessary to initiate fracturing would ordinarily be equal to or greater than those imposed by the overburden. In tectonically relaxed areas, such as the Texas and Louisiana Gulf Coast, the plane of least stress is horizontal. In this case fractures will be vertical and will generally be formed at a pressure less than that imposed by the overburden.

Overburden pressures are commonly assumed to build up at a rate of 1 psi per foot of depth *(23,59)*. The Subcommittee on Disposal of Radioactive Waste of the American Petroleum Institute *(55)* has stated that most formations will fracture hydraulically when fluid pressure in the range of 0.6 to 1.0 psi per foot of depth is exerted in the well bore at the injection horizon.

Petroleum industry experience with water injection wells *(59,60)* has shown that anomalous increases in intake capacity of these wells occur at some critical input pressure. What occurs at this pressure is not certain in every case, since the increased intake of injection wells could result from:

1. Horizontal parting between adjacent vertical strata,
2. opening of pre-existing cracks or joints,
3. compaction of shales adjacent to or in the receiving formation,
4. yielding of packers *(59,60)*.

There is, however, agreement that the critical input pressure is generally the pressure at which rupture of the receiving formation (hydraulic fracturing) occurs *(60)*.

Critical input pressures have been found to range from 0.47 to 1.43 psi per foot of depth in the Bradford area of Pennsylvania *(59)* and from 0.52 to 1.82 psi per foot of depth in various shallow mid-continent water injection wells *(60)*. Values as low as 0.47 are considered to be anomalously low by Yuster and Calhoun *(59)*. Few of the critical input pressures listed by the above-cited writers are less than 0.80 psi per foot of depth, while the majority are greater than 1.00. The estimated critical input pressure or the safe injection pressure for a waste injection well would seem, therefore, to be greater

than about 0.5 psi per foot of depth. The minimum input pressure that could cause hydraulic fracturing in a saturated column of rock would be that which would just exceed the hydrostatic pressure. The hydrostatic pressure of a column of fresh water increases at about 0.43 psi per foot of depth. There is, however, no way of predicting in advance exactly what the critical input pressure will be in an injection well, but it can be estimated from oilfield experience in some areas. Grandone and Holleyman *(60)* concluded that, though use of an overburden factor of 1.00 (pressure of 1 psi per foot of depth measured at the formation face) is satisfactory for estimating the critical input pressure for most oilfield water flood projects tested in the Kansas-Oklahoma area, it is too high for many projects in North Texas. A method of testing injection wells to establish their critical input pressure is described on page 20. When the limiting value of input pressure has been estimated or determined, the life of the injection horizon can be computed as described on page 19.

Rate of pressure increase. The basic equation describing hydraulic flow through porous media is the Darcy equation, which can be written as:

$$Q = \frac{AK}{\mu}\frac{\Delta h}{L} \qquad (2)$$

where:

Q = volume rate of flow
A = average cross-sectional area perpendicular to lines of flow
K = coefficient of permeability
μ = viscosity of fluid
Δh = fluid potential loss along flow path
L = distance along direction of flow

The equation for steady-state radial flow of an incompressible fluid outward from a completely penetrating well can be developed as follows (see Figure 2):

$$Q = \frac{AK}{\mu}\frac{dh}{dr}$$

Since $A = 2\pi rb$

$$Q = \frac{2\pi rbK}{\mu}\frac{dh}{dr}$$

Setting limits

$$Q \int_{r_w}^{r_e} \frac{dr}{r} = \frac{2\pi bK}{\mu} \int_{h_w}^{h_e} dh \qquad (3)$$

Integrating

$$Q = \frac{-2\pi bK\ (h_w - h_e)}{\mu \log_e (r_e/r_w)}$$

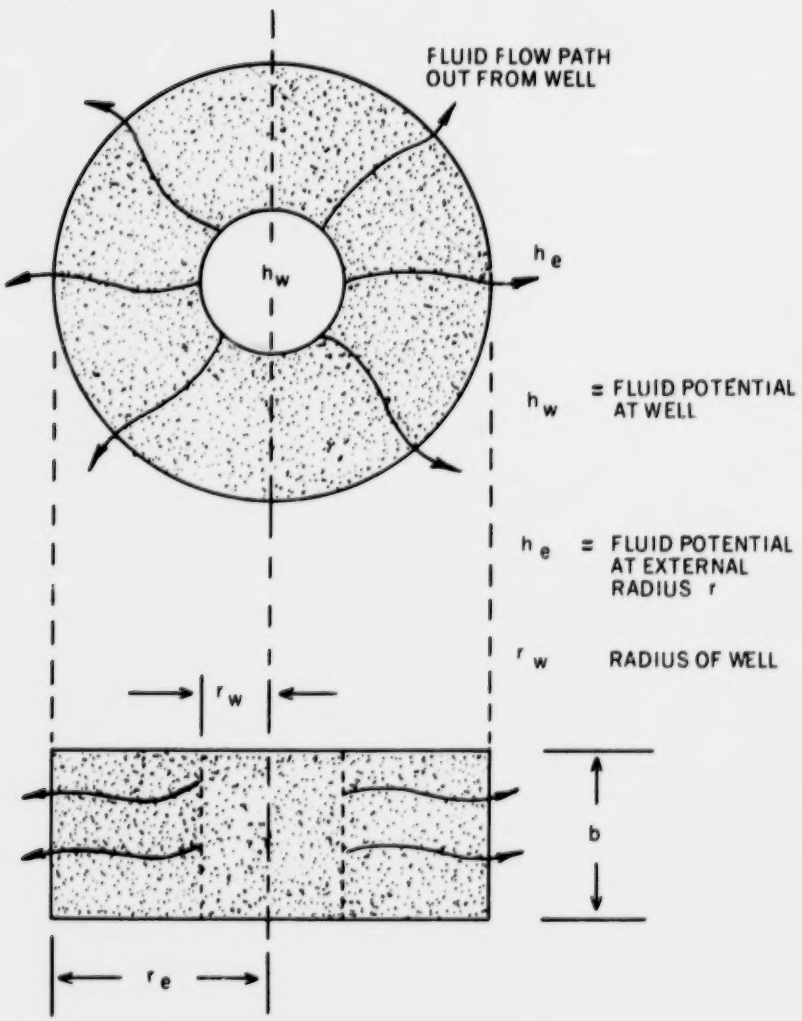

Figure 2. Radial flow outward from a completely penetrating well.

Since equation 3 is an equilibrium flow equation, time does not appear in the equation and no rate of pressure buildup can be computed. Obviously, however, as a constant fluid potential front moves outward from an injection well to some larger radius (r_e), the potential at the well bore (h_w) must increase, if the injection rate (Q) is held constant. Equation 3 shows that once equilibrium flow has been established throughout an aquifer, no further pressure increase would be expected if the physical conditions do not change.

The rate of pressure increase that occurs before equilibrium flow has been established can be computed from nonequilibrium flow equations, as shown by Theis *(61)* and deLaguna and Blomke *(62)*. If the injection horizon is extensive enough to be considered as infinite and is homogeneous and isotropic, the pressure increase at the bore of a completely penetrating well can be computed *(63,64)* from the formula:

$$\Delta h = 114.6 \frac{Q}{T} \int_{u}^{\infty} \frac{e^{-u}}{u} du \qquad (4)$$

where:

Δh = fluid potential increase in feet of water
Q = rate of injection in gpm
T = transmissibility of aquifer in gpd per foot

$$u = 1.87 \frac{(r_w)^2 S}{Tt} \qquad (5)$$

r_w = effective radius of well in feet
S = coefficient of storage
t = time fluid has been injected at a constant rate in days

Equation 4 cannot be integrated, but after the aquifer characteristics have been determined from pumping or injection tests or by other means, u can be calculated and a well function W(u) determined from tables *(65,66)*. The pressure increase is then computed from

$$\Delta h = \left[114.6 \frac{Q}{T}\right] W(u)$$

Jacob *(64)* has shown that when the time (t) becomes large, equation 4 can be closely approximated by the formula:

$$\Delta h = \frac{Q}{4\pi T} \log_e \frac{2.25 Tt}{(r_w)^2 S} \qquad (6)$$

Equation 6 shows that the pressure in an injection well that penetrates an extensive and uniform aquifer increases logarithmically with time.

Many aquifers suitable for waste injection will probably be extensive and uniform enough to allow application of the above-cited equations. Equations that have been developed by ground-water hydrologists for many other aquifer conditions have been reviewed by Wenzel *(65)*, Ferris and others *(66)*, and Walton *(67)*.

The difficulties in computing injection well life lie in the selection of equations that conform to the fluid flow conditions and to the hydrologic boundaries of the disposal horizon, and in the determination of the average physical properties of the injection horizon.

Injectivity index. According to Grandone and Holleyman *(60)*, an important criterion of the behavior of water input wells is the injectivity index or intake capacity per unit of pressure differential at the injection horizon. This measure of intake capacity can be used to follow the intake characteristics of an injection well and to predict the need for remedial measures *(11)*.

Dickey and Andresen *(68)* and Grandone and Holleyman *(60)* have shown that the behavior of an injection well can be characterized by determination of a "restricted" injectivity index. This index is determined by shutting in an input well until the wellhead pressure is falling very slowly, then injecting water for short intervals at several successively higher pressures. When the rate of injection is plotted against the injection pressure on rectilinear coordinate paper, a straight line is commonly obtained, whose slope is the "restricted" injectivity index.

The injectivity index divided by the thickness of the injection interval gives the specific injectivity index (Figure 3), which is a useful unit for comparing injection well performance *(60)*.

The injectivity index as described above is analogous to the specific capacity of water wells as used in ground-water development *(69, 70)*.

Critical input pressure. If an injectivity test is carried to a high-enough pressure, a point of inflection occurs on the pressure-versus-input curve, indicating an abrupt increase in the water acceptance per unit of pressure (Figure 3). This point of inflection occurs at the critical input pressure, which is generally agreed to be the pressure at which rupture of the strata (hydraulic fracturing?) occurs *(60)*. The concepts of critical input pressure and hydraulic fracturing are further considered in the section concerning factors that restrict ultimate injection capacity.

Grandone and Holleyman *(60)* have shown that injectivity tests can be duplicated, even after the critical input pressure has been exceeded. If so, it seems unlikely that permanent damage can have been done to the confining beds by temporarily exceeding the critical input pressure. The American Petroleum Institute *(55)* has stated that

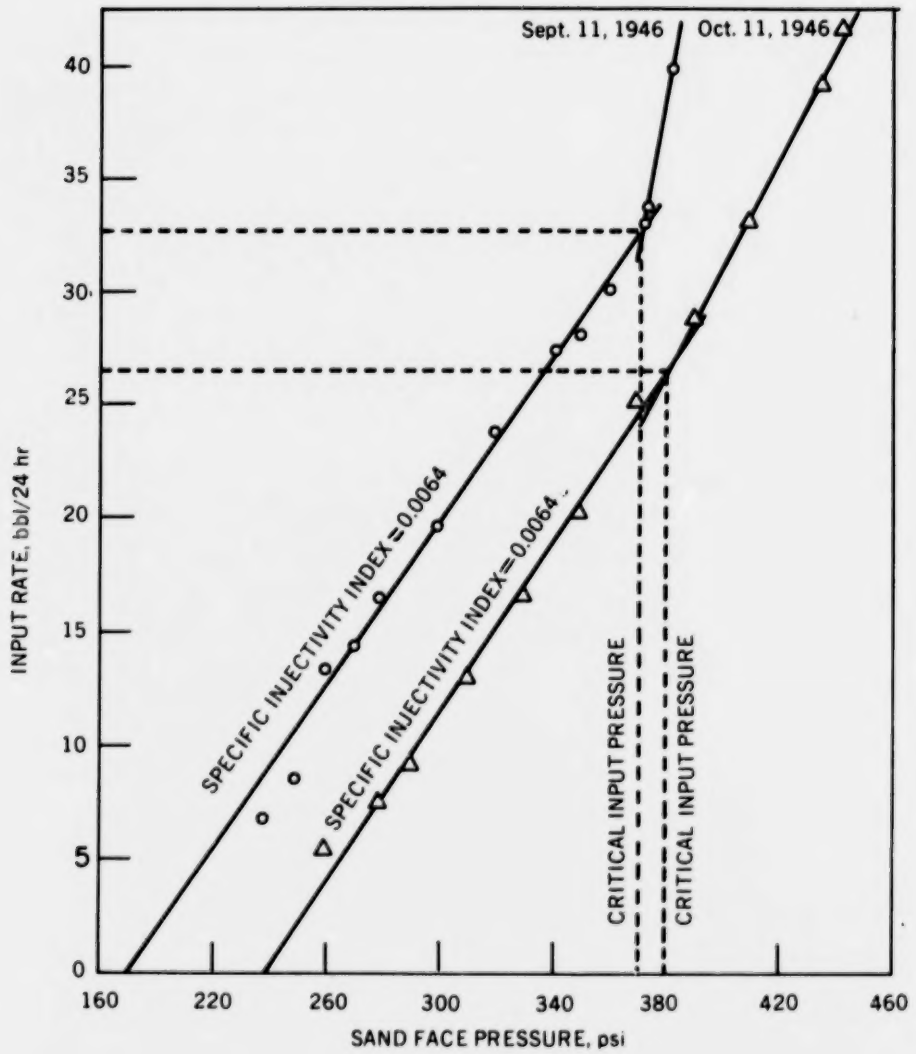

Figure 3. Injectivity characteristics of a water injection well, Kansas (60).

"subsequent reduction in pressure will usually result in closing of the (hydraulic) fractures." If such a test causes no permanent damage to an injection horizon, it could be used to determine the maximum safe injection pressure in a newly drilled waste injection well.

Pumping and injection tests. In-place formation-testing methods offer a possible means of obtaining data that will permit evaluation of the long-term waste acceptance characteristics of an injection horizon. Querio and Powers *(71)* showed that pumping tests provided information that permitted accurate prediction of the behavior of the fluid levels in an observation well near a waste injection well. In other cases, the behavior of injection wells during relatively short periods of time has been extrapolated to indicate their probable long-term performance *(13,14,72)*.

Testing of possible injection horizons can be carried out in deep wells by drill-stem testing, before actual completion of the well. This testing permits determination of reservoir pressure and average permeability, and evaluation of the extent to which drilling has altered the formation characteristics in the immediate vicinity of the well *(40)*. Qualitative and quantitative evaluation of drill-stem test results have been discussed by Lynch *(40)*. His analysis of drill-stem tests was based on pressure build-up data obtained from a single well during production testing and subsequent closing in of the well. The methods applied to production testing can also be applied to injection testing *(73)*.

The pumping tests used by ground-water hydrologists *(66)* are generally designed to be used with observation wells. An exception is the analysis of the recovery of a single pumped well devised by Theis *(63)*. This method allows determination of the coefficient of transmissibility (permeability) and, if the effective radius of the well is known, determination of the coefficient of storage (compressibility).

Analyses of drill-stem tests and pumping tests are generally made by assuming that the reservoir is of infinite extent and enclosed by completely impermeable beds. If pumping or injection tests are of short duration, so that pressure fronts do not extend to hydrologic boundaries, aquifer properties can be determined by using equations that apply to infinite aquifers *(66)*. These properties could not, however, be used to predict accurately the long-term behavior of an injection well if these barriers were within the radius of influence of the well during the longer period of injection.

Horner *(74)* showed that pressure build-up tests could be used to indicate the presence of liner barriers, such as faults, in the vicinity of a well. The distance of a barrier from a well can be determined by equations given by Dolan and others *(75)*. Ferris and others *(66)* and Walton *(67)* discussed analyses used in evaluation of ground-water aquifers in the presence of leaky confining beds and hydrologic boundaries.

Completion of Injection Wells

Well completion consists of inserting the well casing, cementing the casing in place, perforating or slotting the casing if the hole is completely cased, and stimulating the injection horizon. Proper completion of an injection well insures that the injection horizon is segregated from other strata and improves the operating characteristics of the well.

Selection of the completion method can be based on oilfield experience if the injection well is in an oil-producing area, but if it is not,

selection must be made on the basis of areal geological data and data obtained during drilling of the well *(41)*.

Open-hole well completion methods can be used in competent (strong and cohesive) strata (Figure 4) and are advantageous because they are cheaper *(38)*, because they facilitate treatment of the injection horizon in the event of plugging *(41)*, and because no casing is exposed to corrosive waste fluids at the injection horizon.

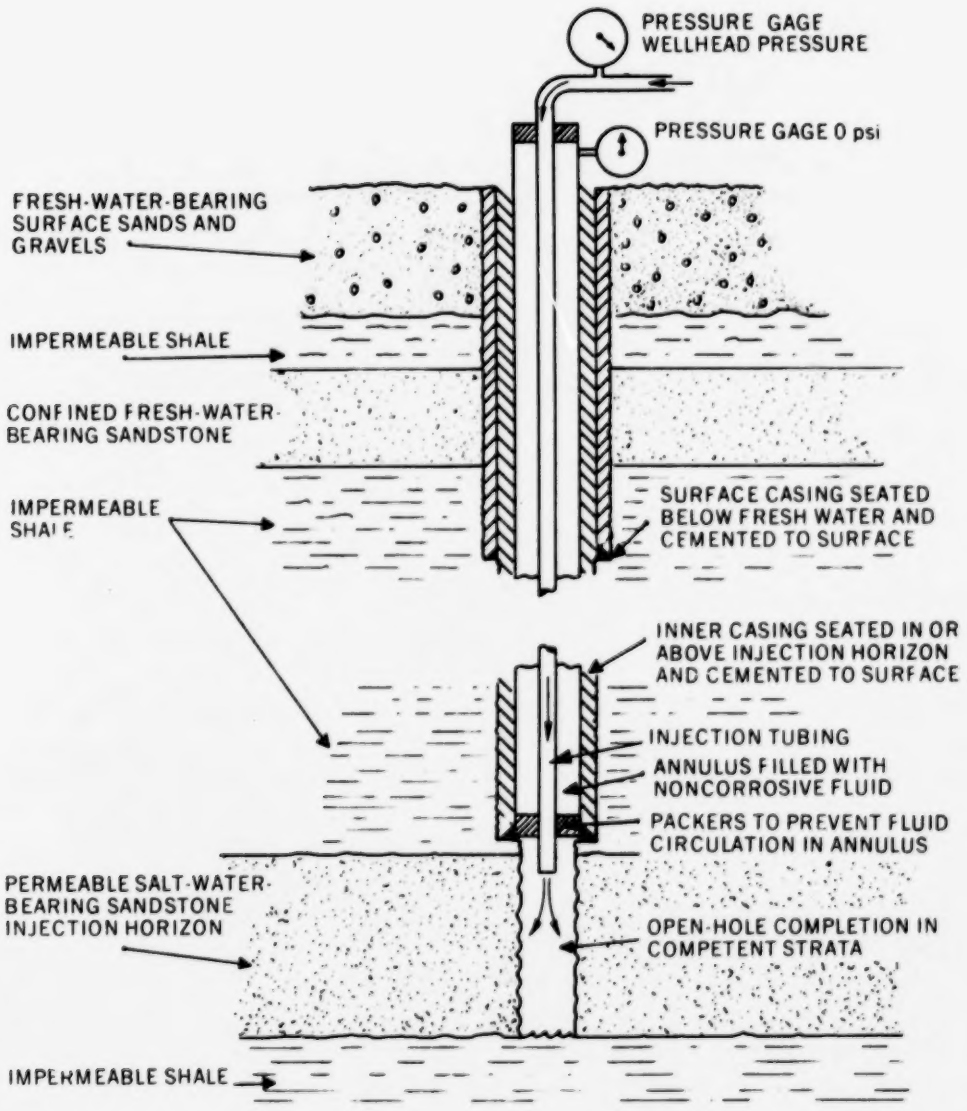
PRESSURE GAGE
WELLHEAD PRESSURE
PRESSURE GAGE 0 psi
FRESH-WATER-BEARING SURFACE SANDS AND GRAVELS
IMPERMEABLE SHALE
CONFINED FRESH-WATER-BEARING SANDSTONE
IMPERMEABLE SHALE
SURFACE CASING SEATED BELOW FRESH WATER AND CEMENTED TO SURFACE
INNER CASING SEATED IN OR ABOVE INJECTION HORIZON AND CEMENTED TO SURFACE
INJECTION TUBING
ANNULUS FILLED WITH NONCORROSIVE FLUID
PACKERS TO PREVENT FLUID CIRCULATION IN ANNULUS
PERMEABLE SALT-WATER-BEARING SANDSTONE INJECTION HORIZON
OPEN-HOLE COMPLETION IN COMPETENT STRATA
IMPERMEABLE SHALE

Figure 4. Schematic diagram of a waste injection well completed in competent sandstone

CASING AND TUBING

The design of a casing program depends on well depth, fluid pressures, type of well completion, expected future remedial work on the well, and in some cases, the expected future drilling time in the casing. In addition to the engineering considerations, state regulatory bodies may have rules concerning the casing of waste injection wells (for example, Texas). Many of these agencies and the Federal Government have regulations governing the casing of oil and gas wells (see Reference 76, chapter 20), and these regulations may, in some cases, apply to waste injection wells.

In deep wells, more than one diameter of casing is necessary. Larger diameter surface casing may extend from a few hundred to several thousand feet below the surface (Figure 4). Surface casing is used to protect fresh-water aquifers from contamination by salt water from deeper strata, and its design is, therefore, often regulated by law.

Casing of smaller diameter is run through the surface casing to the top of the disposal horizon (open-hole completion) or to the bottom of the hole (completion by perforating) to close off salt-water aquifers and zones of incompetent rock and protect gas- and oil-bearing strata. State and Federal laws dictate, in some cases, the seating, cementing, and pressure testing of this casing (intermediate and production casing) in oilfields.

If waste is pumped through the casing without tubing, corrosion can be a problem. Casing can, however, be internally coated with cement or plastic to prevent corrosion.

Casing can develop leaks as a result of corrosion or excessive pressure. Casing failure can be detected by radioactive tracer injection and subsequent gamma ray logging *(77,78)*, by flowmeter logging *(79)*, or by caliper surveys.

Where corrosive wastes are to be disposed, tubing should be used inside the casing, since it can be readily replaced whereas corroded casing cannot. Tubing can be of a corrosion resistant alloy or of plastic, or ordinary tubing can be plastic or cement lined. Epoxy-resin plastic tubing, completely resistant to corrosion, has been successfully used in salt-water disposal wells *(37)*.

Table 2. REGULATORY BODIES CONTROLLING THE CEMENTATION OF WELLS DRILLED FOR OIL OR GAS IN THE MAJOR OIL- AND GAS-PRODUCING STATES OF THE UNITED STATES *(76)*

State	Regulatory body	Location
Alabama	Oil and Gas Board	University
Alaska	Oil and Gas Conservation Commission	Juneau
Arizona	Arizona State Lands Commission	Phoenix
Arkansas	Arkansas Oil and Gas Commission	El Dorado
California	Department of Natural Resources—Oil and Gas Division	San Francisco
Colorado	Oil and Gas Conservation Commission	Denver
Florida	Board of Conservation	Tallahassee
Georgia	Oil and Gas Commission	Atlanta
Idaho	Bureau of Mines and Geology	Moscow
Illinois	Department of Mines and Minerals	Springfield
Indiana	Indiana Department of Conservation—Division of Oil and Gas	Indianapolis
Kansas	State Corporation Commission	Wichita
Kentucky	Department of Mines and Minerals	Lexington
Louisiana	Louisiana Department of Conservation	Baton Rouge
Maryland	Department of Geology, Mines, and Water Resources	Baltimore
Michigan	Michigan Conservation Commission—Oil and Gas Division	Lansing
Mississippi	Mississippi Oil and Gas Board	Jackson
Missouri	Missouri Geological Survey	Rolla
Montana	Oil and Gas Conservation Commission	Helena
Nebraska	Nebraska Conservation and Survey Div.	Lincoln
Nevada	Nevada Oil and Gas Conservation Commission	Reno
New Mexico	New Mexico Oil Conservation Commission	Santa Fe
New York	State Science Service	Albany
North Carolina	Department of Conservation and Development	Raleigh
North Dakota	Industrial Commission of North Dakota	Bismarck
Ohio	Department of Industrial Relations Division of Mines	Columbus
Oklahoma	Corporation Commission of Oklahoma	Oklahoma City
Oregon	Department of Geology and Mineral Industries	Portland
Pennsylvania	Department of Mines—Oil and Gas Division	Harrisburg
South Dakota	Oil and Gas Board	Pierre
Tennessee	Department of Conservation	Nashville
Texas	Texas Railroad Commission—Oil & Gas Div.	Austin
	General Land Office—Oil and Gas Div.	Austin
Utah	Oil and Gas Conservation Commission	Salt Lake City
Virginia	Department of Labor and Industry	Big Stone Gap
Washington	Oil and Gas Conservation Commission	Olympia
West Virginia	Department of Mines—Oil and Gas Div.	Charleston
Wyoming	Wyoming Oil and Gas Conservation Commission	Cheyenne
Federal	United States Geological Survey	Washington, D.C.

Packers can be set at the bottom of a casing string (Figure 4) to segregate it completely from the corrosive fluids that flow through the tubing or from the high pressures that may be used in tubing. Packers are recommended *(37)* only where conditions require their use, since they may become corroded and difficult to remove.

CASING CEMENTING

The annulus between the rock strata and the casing is cemented to protect the pipe from external corrosion by subsurface waters, increase casing strength, prevent mixing of the waters contained in the aquifers behind the casing, and prevent waste from being injected into aquifers other than the disposal horizon. Cementing is done by oilfield service companies, which have extensive experience in this technique. According to Baker *(80)*, in the past 35 years over 2 ½ million wells have been cemented by one service company.

Since the cementing of casing in deep wells is performed, in part, to protect potable water and oil- and gas-bearing strata, oil well and gas well cementing is subject to regulation by state and Federal agencies (Table 2). A summary of cementing regulations as applied to oil wells and gas wells has been published by the American Petroleum Institute *(76)*. These regulations may apply, in some cases, to deep waste injection wells.

Oil well- and gas well-cementing regulations generally provide for completely filling the annular space between the surface casing and the wall of the hole with cement, and for cementing a minimum number of feet at the base of the interior (production) casing. The American Petroleum Institute *(55)* has suggested that the main string of casing, for a well to dispose radioactive waste, be set in a hole of sufficient diameter to permit at least 1 inch of cement to be placed outside the pipe for its entire length (hole diameter at least 2 inches greater than casing outside diameter).

Oil well- and gas well-cementing regulations often provide for an appropriate well log to insure that cementing has been accomplished and for pressure testing of a cemented well to insure that leakage does not occur behind improperly cemented casing. Tests for improperly cemented casing can also be made by injecting radioactive tracers in gas *(81,82)* or liquid *(77,78)* in conjunction with gamma ray surveys.

WELL STIMULATION

Increasing the acceptance rate of injection wells by chemical or mechanical treatment may be desirable. A common chemical treatment is the injection of acid (hydrochloric, hydrofluoric, etc.) into the disposal horizon to dissolve calcium carbonate or other acid-soluble material. Acidizing is obviously most effective in limestones or dolomites but is also used in sandstones to dissolve the carbonates, or flocculate or destroy clay minerals *(83)*. Detergents have also been used to increase injection well acceptance *(84)*.

Common oilfield mechanical treatments are scratching, swabbing, washing, and underreaming the well bore; "shooting" an uncased stratum with explosives; or hydraulically fracturing either an open horizon or a cased and perforated horizon *(37)*. "Shooting" a well consists of using nitroglycerin or other explosives to remove deposits from the strata and fracture them. The possibility of damaging the casing, and the cleaning out necessary after shooting discourage the use of this method *(37)*.

Hydraulic fracturing is used in the oil industry to increase the acceptance rate of brine disposal and water flood input wells. This technique has been suggested for increasing the injection rate of industrial-waste-disposal wells *(71,80,85)*. That this method is entirely safe for waste disposal wells is not certain, since some authors *(52,53)* have suggested that vertical fractures (produced by hydraulic fracturing) that extend through the cap rock could permit fluids to escape into vertically adjacent aquifers.*

OPERATION OF INJECTION WELLS

Permeability Reduction During Operation

An important problem in the injection of waste into deep aquifers is the danger of reduction in permeability of the disposal horizon during operation, which could occur as a result of the plugging of

*The American Petroleum Institute Subcommittee on the Disposal of Radioactive Waste **(55)** stated that "Experience in the petroleum industry shows that damage of this kind (hydraulic fracturing) is unlikely to result in the rupture of overlying rocks."

pores by suspended solids or entrained gas, or through reactions between injected and interstitial fluids or between injected fluids and aquifer minerals.

Plugging of the injection horizon in the immediate vicinity of the injection well bore by suspended solids is a common problem in oilfield operations. These solids may be present initially, or when waters that are in chemical equilibrium are subjected to changes in temperature, pressure, or gas content, dissolved constituents, particularly manganese or iron, may precipitate *(47,86)*. These precipitates can plug the injection well face or pores near the face. Other solids can precipitate through reaction of corrosive waters with pumping equipment and well casing or tubing *(86,87)*. Entrained and dissolved air increases the corrosiveness of water *(47,86)*, and entrained air could also act directly to plug the pores of the injection horizon, since the permeability of a sandstone to water containing only a small amount of entrained gas is much less than its permeability to water alone *(88)*. Water to be injected in oilfield operations is, therefore, routinely treated to remove suspended solids and dissolved iron and manganese, and deaerated before injection to prevent corrosion and plugging problems.

Plugging at or near the well bore can also be caused by bacteria, algae, and mold on the sand particles *(89,90)*; by the sheaths of capsulated bacteria and iron bacteria *(90)*; and by sulfate-reducing bacteria that produce H_2S, which reacts with iron to form insoluble FeS_2. Bacteria can be detected by the procedures suggested by the American Petroleum Institute *(91)*, and can be controlled with various chemicals *(90,92)*, but caution should be exercised since many otherwise good bactericides produce insoluble products when added to oilfield brines *(89)*.

Stahl *(93)* briefly reviewed the problem of the incompatibility of injected and interstitial waters and concluded that, while older literature mentioned the possibility of plugging by insoluble precipitates, laboratory evidence to that time was contradictory. Work by Laird and Cogbill *(94)* showed that severe permeability reduction resulted from the simultaneous injection of incompatible waters into large cylindrical cores. Bernard *(95)* found, on the contrary, that little permeability reduction was caused by the simultaneous injection of incompatible waters or by the displacement of one water with another incompatible with the first. The effect of incompatibility on permeability reduction is apparently related to the degree of mixing of the incompatible waters.

Many recent theoretical and experimental studies have been concerned with the dispersion of fluid boundaries during displacement of a fluid with another miscible one in porous media. Harleman

and others *(96-98)* and Nielsen and Biggar *(99-101)* have reviewed much of this literature and have presented new experimental evidence showing that, even in homogeneous isotropic media, streamers of the displacing fluid penetrate into the displaced fluid in advance of the main boundary. Some chemical mixing of displacing and displaced fluids would, therefore, be expected to occur during this dispersion.

Hence, reduction in permeability to injected water could occur through precipitation reactions between waste water and interstitial water or waste water and aquifer minerals, through production of gaseous reaction products, through development of reaction coatings on aquifer minerals, or through dispersion of clay minerals as a result of ion exchange or salinity reduction in interstitial waters.

The chemical character of waste water would be expected to be somewhat different at each injection site. The chemical character of deeply buried subsurface waters has been studied in oilfields, and many analyses of oilfield waters have been published *(e.g., 102-111)*.

Oilfield waters commonly range in salinity from practically fresh water to water containing 300,000 ppm dissolved salts. According to Levorsen *(23)*, the greatest recorded concentration is that noted by Case *(112)* in the Salina Formation of Michigan where the brine contained 642,798 ppm dissolved salts. The most common dissolved constituents in oilfield waters are sodium, calcium, magnesium, and potassium, which commonly combine with chloride, sulfate, carbonate, and bicarbonate. Other constituents listed by various writers as present in oilfield waters are free CO_2 and H_2S, iron, barium, lithium, strontium, iodine, bromine, boron, copper, manganese, silver, tin, vandadium, zinc, lead, cadmium, fluorine, phosphorus, silica, and nitrogen. Relatively large concentrations of strontium and barium have been found in some oilfield waters *(113,114)*. Other chemical elements would be expected to be present in addition to those listed above, since many oilfield waters are derived from sea water, which at present contains other elements.

As was pointed out by Stiff *(115)*, the basic chemical characteristics of the water from a given aquifer can be similar over a large area. The character of the water from various aquifers can, however, vary widely as can the characteristics of the water within a given horizon in some cases *(116)*. Probably, a safe assumption is that, for a preliminary estimation of water compatibility, the water analysis from a given aquifer within a short distance of a possible injection well site would be representative of that at the injection site.

MacLeod *(17)* and Selm and Hulse *(117)* have listed the reactions that can cause plugging precipitates to form:

1. Precipitation of alkaline earths such as calcium, barium,

strontium, and magnesium as relatively insoluble carbonates, sulfates, orthophosphates, fluorides, and hydroxides;*

2. precipitation of heavy metals such as iron, aluminum, cadmium, zinc, manganese, chromium, and others as insoluble carbonates, bicarbonates, hydroxides, orthophosphates, and sulfides;
3. precipitation of oxidation reduction reaction products;
4. polymerization of resin-like materials to solids under aquifer temperature and pressure.

Henkel *(10,11)* reported testing brine and waste water compatibility by allowing a mixture of the two liquids to stand for from 8 to 24 hours at the approximate aquifer temperature. Stahl *(93)* stated that this method is common practice before starting a secondary recovery process in the oil industry. The mixture is considered compatible if it remains free of precipitates. This criterion may not be entirely satisfactory in all cases, since reactions may require considerable time for completion *(7,17)*, and reaction products other than precipitates, such as gases, can cause important reduction in permeability to water.

In testing the compatibility of aquifer water and waste, the use of water from the actual disposal horizon is desirable since even small differences in brine characteristics can cause unexpected reactions *(15)*. In addition, synthesizing a particular brine in the laboratory may be impossible, since natural brines apparently supersaturated in certain salts are not uncommon *(3)*.

In circumstances where waste water and aquifer water are incompatible and treating the waste to make it compatible is impossible or impractical, a front of nonreactive water might be injected ahead of the waste water to form a buffer between the waste and the aquifer water *(7,15)*.

A small number of minerals comprise nearly the entire mass of sandstone aquifers. The average sandstone, as determined by Clarke *(120)*, consists of 66.8 percent SiO_2 (mostly quartz), 11.5 percent feldspars, 11.1 percent carbonate minerals, 6.6 percent micas and clays, 1.8 percent iron oxides, and 2.2 percent other minerals. Limestone and dolomite aquifers are primarily $CaCO_3$ and $CaMg(CO_3)_2$, but impure ones may contain as much as 50 percent noncarbonate constituents such as SiO_2 and clay minerals.

Quartz, the main constituent of sandstones, is the least reactive of the common minerals, and for all practical purposes can be considered nonreactive except in highly alkaline solutions *(85)*. Clays have been demonstrated to react with highly basic or highly acidic solutions *(121-125)*. A waste would not necessarily need to be highly acidic

*Heck (114) has discussed the problem of precipitation of $BaSO_4$; Stiff and Davis (118), $CaSO_4$; and Stiff and Davis (119), $CaCO_3$.

to attack an aquifer mineral, since some relatively weak acid may strongly attack certain clay minerals *(121,123,126)*. The degree of reaction of feldspars and micas with injected solutions is not certain, but some reaction would no doubt occur *(85)*.

Sandstone aquifers are often cemented with carbonate minerals, which react with acid solutions. Reaction of acid wastes with the carbonate cement in sandstone would cause an evolution of CO_2 that could both increase the pressure and reduce permeability. In the special case of acid aluminum nitrate wastes, Roedder *(85)* has shown that the reaction of the waste with $CaCO_3$ results in a gelatinous precipitate that would plug the pores in a sandstone containing sufficient carbonate minerals. Sandstones also commonly contain gypsum and limonite as cementing material, and these two minerals can be dissolved and reprecipitated to cause blocking of pores *(127,128)*

The brines in deep limestone or dolomite aquifers will, in most cases, be in chemical equilibrium with the aquifer, and precipitation or solution will not be occurring. If, therefore, injected wastes are at a lower pH than aquifer waters are, solution of the carbonate aquifer material will occur. This reaction could be beneficial, as long as no gelatinous precipitates result, such as those that occur when acid aluminum nitrate wastes react with $CaCO_3$. If injected wastes mix with aquifer water and raise its pH, dissolved salts could precipitate and cause plugging of the pores in the limestone.

Clay minerals are common constituents of sedimentary rocks. Roedder *(85)* stated that sandstones containing less than 0.1 percent clay minerals may not exist anywhere in the United States, except possibly in small deposits of exceedingly pure glass sand. Clay minerals are known to reduce the permeability of sandstone to water as compared with its peremeability to air *(129,130)*. The degree of permeability reduction to water as compared with air is termed the water sensitivity of a sandstone by Baptist and Sweeney *(130)*.

The water sensitivity of clay-bearing sandstones increases with decreasing water salinity, decreasing valence of the cations in solution, and increasing pH of the water *(129, 131, 132)*. The water sensitivity of a sand depends on the type of clay mineral as well as the amount. Hughes *(133)* pointed out that the properties that cause clay minerals to reduce sandstone's permeability to water are exhibited by montmorillonite to a marked degree, by illite to a lesser degree, and by kaolinite to a relatively unimportant degree. Concepts that can be used to explain the above-mentioned observations have been discussed by Van Olphen *(134)*.

Water sensitivity of sandstones can be determined directly by permeability tests with various waters and air or indirectly by X-ray diffraction, differential thermal analysis, or water vapor absorption measurements *(130, 135)*.

Optimum permeability of water-sensitive sandstones can be maintained by injecting waters of high salinity and low pH, but acidic brines present corrosion problems. Torrey *(136)* has suggested an alternative procedure that consists of acidizing a well and then mixing a nonionic detergent with the injected water.

Monitoring Injection Wells

It would seem desirable to monitor injection wells and the travel of injected waste in order to detect failure of the well casing or cement, escape of waste through fractured or faulted cap rocks or through other abandoned or operating wells, and loss of permeability in the injection horizon during injection.

PRESSURE MONITORING

As fluid is injected into a confined aquifer, the pressure needed to maintain a constant injection rate increases with time. The injectivity index* should not, however, change unless the physical character of the reservoir is changed.

A sudden increase in the intake rate of an injection well, when no remedial treatment has been performed, probably indicates the opening of horizontal or vertical fractures in the injection horizon and possibly in the confining beds *(53,60)* or the failure of well facilities, such as casing, cement, or packers *(59)*. A decrease in injectivity index probably indicates decreased permeability at or near the face of the injection horizon as a result of plugging by suspended solids or chemical precipitates, the dispersion of swelling clays, and so forth.

Pressure monitoring of the fluid column between injection tubing and well casing is suggested as a means of injection well monitoring by the American Petroleum Institute *(37)*. If a packer is used to segregate the fluid in this annular space from the fluid being injected (Figure 4), monitoring of the pressure should permit detection of tubing or packer leaks. This monitoring was required by the Michigan State Water Resources Commission *(137)* for an oil refinery waste injection well.

OBSERVATION WELLS

A nondischarging well constructed in the immediate vicinity of a waste injection well for the purpose of monitoring the travel of injected wastes may be of limited practical value. This kind of observation well in the disposal horizon will monitor only a narrow band of flowing

*Injectivity index $= \frac{\text{input rate}}{\text{differential pressure at injection horizon}}$

liquid, at the most, twice the width of the well itself *(61)*. Thus, an observation well would have to be rather accurately located downgradient from an injection well, if the flow path of waste is narrow.

Probably, as Theis *(138)* has pointed out, in a formation of low permeability, injected waste would initially assume the shape of an expanding cylinder, then, over a long period of time, disperse over a zone thousands of feet wide. On the other hand, in a very permeable formation, injected waste might tend to flow away from the injection well in narrow channels of high permeability rather than disperse evenly. In either case nondischarging observation wells would probably not be helpful for monitoring waste travel. In highly permeable formations, the observation well might not intercept the flow path of the waste, and in formations of low permeability, the waste would disperse so slowly that it would not reach observation wells for many years.

Discharging water wells in fresh-water aquifers above an injection horizon would provide a means of detecting leakage from the disposal horizon; these wells should be carefully watched for signs of contamination. Leakage could occur through fractured or faulted confining beds, through corroded or ruptured well casing, behind the casing in an improperly cemented well, or through improperly plugged abandoned wells that penetrate the disposal horizon.

Heat Generation

Heat generated by the decay of injected radioactive waste material may be a serious problem in the disposal of this waste into deep wells *(85,138)*, but this has not been reported as a problem in the injection of other wastes.

Some of the theoretical aspects of the heat generation problem have been considered by Kaufman and others *(51)*, Roedder *(85)*, Birch *(139)*, and Skibitzke *(140)*. Hess and others *(54)* feel that the problem of heat generation in the disposal of radioactive waste could be solved by dilution, since the volume of waste is small enough that dilution ratios ranging from 1:1 to 1,000:1 are feasible.

INJECTION WELL FAILURE

Injection wells can fail in different senses. The most important type of failure, from a public-interest viewpoint, would be one that could involve contamination of fresh water or other valuable natural resources. Other types of failure, such as plugging of the injection horizon, can also occur.

The Kansas State Board of Health *(4)* has reported that about 10 cases of habitual failure in oilfield brine injection wells are reported to their office each year. Well failure is attributed primarily to excessive injection pressure in combination with inadequate casing and improper well cementation. This type of failure could result in the contamination of ground water.

Ground-water contamination from oilfield brines has been reported as having possibly occurred through improperly plugged abandoned wells or through wells that injected brine into near-surface horizons at high pressure *(141)*. Hallden *(82)* discussed an instance of ground-water contamination above a gas storage reservoir. Contamination in this case could have been a result of leakage through abandoned wells, leakage around improperly cemented wells, or leakage through permeable or faulted confining beds. The Dow Chemical Company *(142)* attempted to inject brine into a subsurface horizon but abandoned this procedure because the saline water was returning to the surface through other wells that pierced the injection horizon.

In addition to the above-mentioned types of failure, contamination of ground water or other natural resources could occur through lateral movement of injected fluids within the injection horizon.

The failure of injection wells as a result of improper construction is avoidable since the engineering knowledge that will virtually assure the reliability of well facilities has been developed. The escape of injected waste through abandoned wells that penetrate the injection horizon could, in most cases, be prevented by adequate study of the records of state agencies and oilfield information services. Abandoned wells that are not registered exist, however, in some states, and these wells can, if improperly plugged, provide a mechanism for leakage of fluid into the strata above or below the injection horizon. The leakage of injected waste through the strata that confine the injection horizon is not likely to occur if competent geologic evaluation of the injection horizon is performed.

Mau stated in the Industrial Wastes Forum *(5)*, that "Kansas has more brine-disposal wells than all the rest of the states combined . . . . if brines are disposed of into mineral-like water formations below an impervious geological formation, no danger will be afforded to a water supply provided the injection well is properly constructed."

ECONOMICS OF INJECTION WELL CONSTRUCTION AND OPERATION

A report by Koenig *(38)* summarized the estimated cost of injection well construction and operation according to information available from the petroleum industry. He considered well construction costs, including drilling, testing, and completing; pumping equipment costs;

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water-conditioning-facility costs; and the operating cost of waste treatment and injection. These costs were computed for the 81 possible combinations that can arise from three cases for each of four variable parameters chosen for study. The variable parameters and the cases examined were well depth (3,000, 7,000, and 12,000 feet), daily volume (1,000, 100,000, and 2 million gpd), specific gravity of waste (1.00, 1.005, and 1.187), and injection pressure (0, 260, and 900 psi). The parameters selected by Koenig appear to be realistic when compared with existing deep-well injection facilities described in published articles.

Fixed costs include those for well construction, pumping equipment, and water-conditioning facilities. According to Koenig's analysis, fixed costs would account for 50 to 80 percent of the total cost of injecting a unit volume of waste in a 1,000 gpd system. The percent contribution of fixed costs increases as the injection rate decreases and would be expected to account for nearly the total cost per volume of injected waste in systems that inject only small amounts of waste.

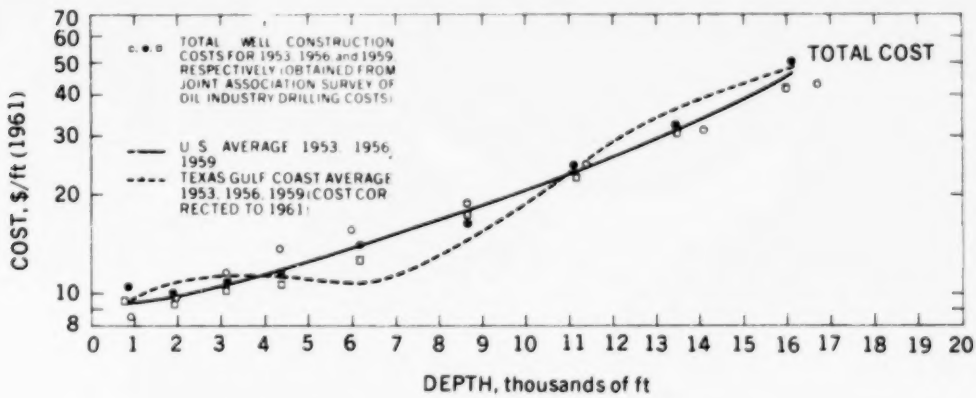
TOTAL WELL CONSTRUCTION COSTS FOR 1953, 1956 and 1959, RESPECTIVELY (OBTAINED FROM JOINT ASSOCIATION SURVEY OF OIL INDUSTRY DRILLING COSTS)
U.S. AVERAGE 1953, 1956, 1959
TEXAS GULF COAST AVERAGE 1953, 1956, 1959 (COST CORRECTED TO 1961)
TOTAL COST
COST, $/ft (1961)
70
60
50
40
30
20
10
8
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
DEPTH, thousands of ft

Figure 5. Cost of oil and gas well construction (38).

The total average cost of well construction alone, based on data from the petroleum industry, is summarized in Figure 5. This cost compares closely to Koenig's synthetically computed total well construction costs, which are a summation of the costs, obtained from various sources, of drilling, testing, and completing a well.

Fixed costs of centrifugal and triplex pumping equipment are shown in Figure 6. In preparing this figure, Koenig computed the costs of triplex pumps on the assumption that motors were available in a continuous series of horsepowers, though these pumps were actually available only in the two horsepowers indicated. The selection of pumps for waste injection is based primarily on the quantity of waste to be injected, the wellhead injection pressure, the corrosiveness of the waste, and the relative economics of the various pumps available.

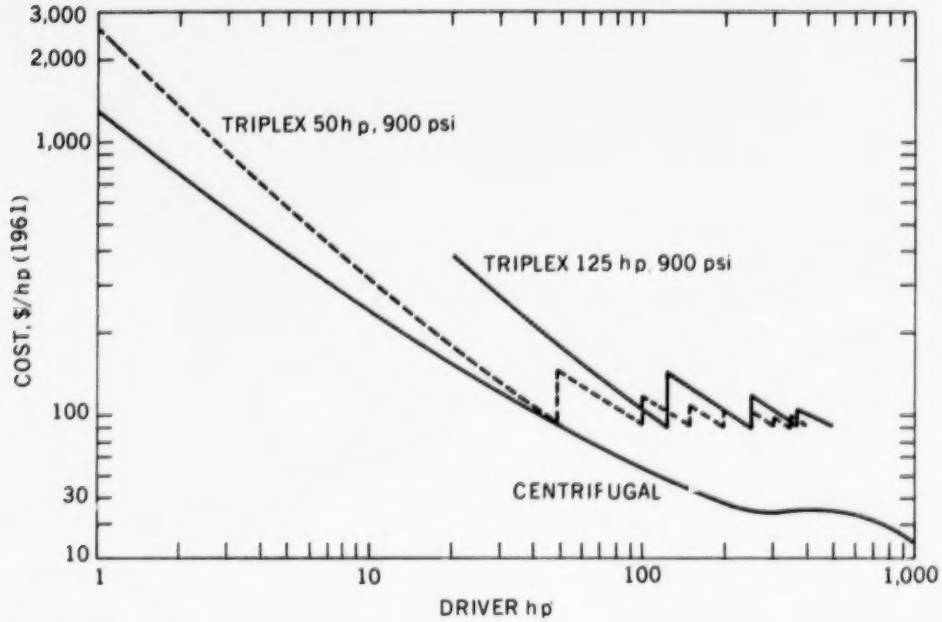

Figure 6. Cost of pumping equipment in 1961 (pump, motor accessories installed and wired) (38).

Centrifugal pumps have in the past been suitable for low-pressure (ordinarily less than 300 psi) service *(37)*, but single-stage centrifugal pumps have recently become available that are capable of operating at relatively high pressures *(147)*. Centrifugal pumps are considered by Donaldson *(143)* to be better suited for waste injection systems because they offer more flexibility, lower maintenance cost, minimal leakage, and greater safety.

Fixed costs of water-conditioning facilities, based on 11 existing oilfield brine treatment plants in East Texas and California, are shown in Figure 7. The East Texas conditioning system, upon which the cost in Figure 7 is based, consists of chemical flocculation, sedimentation, filtration, and chlorination. The California plants are similar, but do not use chemical coagulation. Chemical treatment with chlorine and polyphosphate is employed in the California plants for control of microorganisms and scale.

Koenig *(38)* concluded that the injection capacity of a well has the greatest influence on unit costs, that well depth is second in importance and pressure third, and that density of the waste has the least effect. His analysis is useful in placing the cost of waste disposal by deep-well injection in the proper perspective, but his data are necessarily based on the average cost of oil well construction and completion and on the cost of oilfield brine pre-injection treatment. The cost of injection well construction and completion and of industrial-waste pre-injection treat-

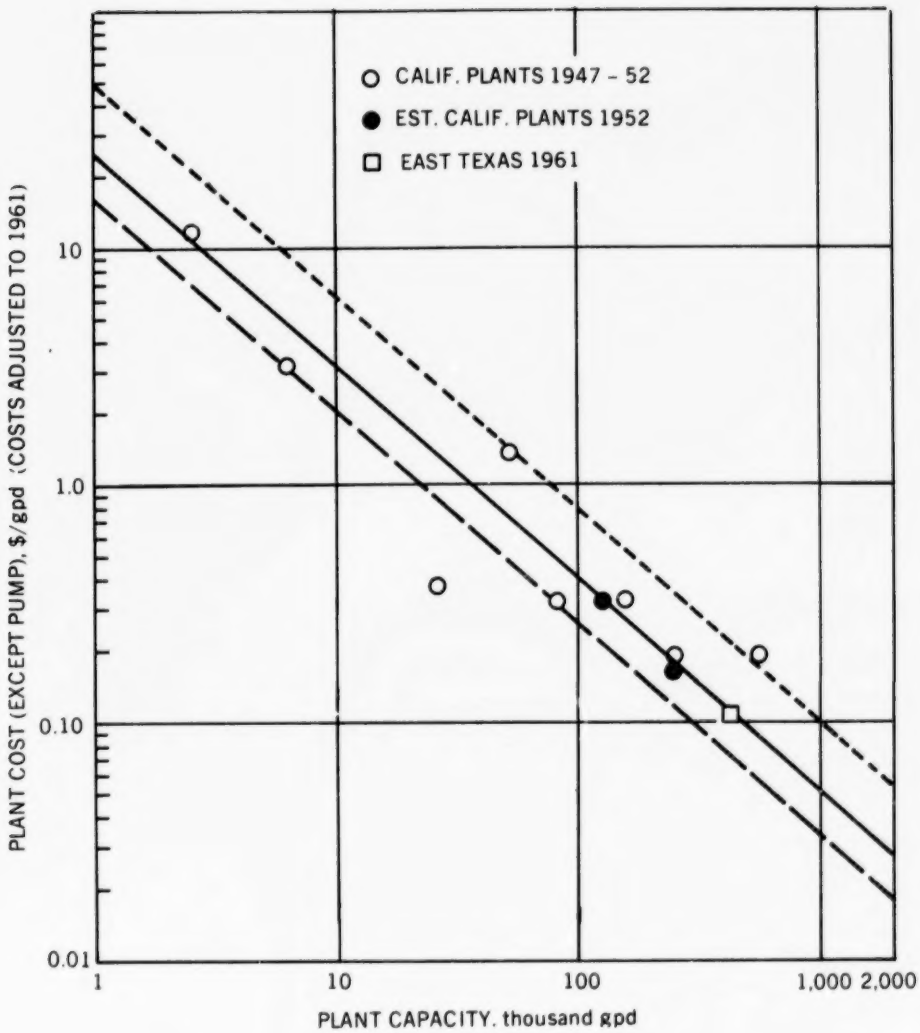

Figure 7. Cost of plants for conditioning injection water (38).

ment would exceed his estimates, when these wells are located away from petroleum-producing areas, or when special well construction and completion or waste treatment techniques are required, as might often be the case. Cost items not considered by him include those that might be incurred for periodic well stimulation and replacement of corroded well tubing.

The cost of existing injection well systems as listed by Donaldson *(143)* and as reported in other published articles cannot be closely compared with the estimated cost of these systems, according to Koenig's *(38)* data (Figures 5, 6, and 7), since published injection well cost figures are not usually broken down into major cost components.

Donaldson *(143)* listed the total cost of five injection well systems with wells that range in depth from 1,472 to 1,960 feet as $30,000, $135,000 (for two wells), $300,000, $400,000, and $562,000. Figure

Table 3. REQUIREMENTS OF THE INDIVIDUAL STATES FOR CONSTRUCTION OF A DEEP WASTE INJECTION WELL (AFTER THE CONFERENCE OF STATE SANITARY ENGINEERS, 1964)

State	State agency	Requirements					
		Securing permit	Submission of plans	Filing of plat	Filing written location	Filing log for drilled wells	Filing record of abandonment
Alabama	Water Improvement Commission	Y	Y	Y	-	Y	-
Alaska	Division of Health, DHEW	Y	Y	y	-	Y	-
Arizona		-	-	-	-	-	-
Arkansas	Water Pollution Control Commission	Y	-	Y	-	Y	Y
California	Division of Oil and Gas	-	a	a	-	a	a
Colorado		-	-	-	-	-	-
Connecticut		Not used					
Delaware	Water Pollution Commission	b	b	b	-	-	-
Florida	Board of Health	Y	Y	Y	-	Y	-
Georgia		Do not approve					
Hawaii	Department of Health	-	Y	Y	-	-	-
	Board of Land and Natural Resources	-	-	-	-	-	-
Idaho	Department of Health	-	Y	Y	Y	-	-
	Department of Reclamation	-	-	-	-	-	-
Illinois	Sanitary Water Board	Y	Y	Y	-	-	Y
	Department of Mines and Minerals	-	-	-	-	y	-
Indiana	Stream Pollution Control Board	-	Y	-	Y	-	-
	Department of Conservation	c	-	c	-	Y	d
Iowa	Natural Resources Council	Y	Y	Y	-	Y	-
Kansas	Department of Health	Y	Y	Y	-	Y	-
	Corporate Commission	Y	Y	Y	-	Y	Y
Kentucky	Water Pollution Commission	Y	Y	Y	-	Y	-
	Department of Mines and Minerals	Y	Y	Y	-	Y	Y
Louisiana	Conservation Commission	Y	Y	Y	-	Y	Y
	Board of Health	e	e	e	-	-	e
Maine	Division of Sanitary Engineering, DHEW	f	f	-	-	-	-
Maryland		No information					
Massachusetts	Department of Public Health	-	Y	Y	-	Y	-
Michigan	Water Resources Commission	Y	Y	-	Y	Y	Y
Minnesota	Water Pollution Control Commission	Y	Y	Y	-	Y	Y
	Department of Health	Y	Y	Y	-	Y	-

		[a]	[b]	[c]	[d]	[e]	[f]
Mississippi	Oil and Gas Board			Require brines from oil and gas well to be returned to strata from which they originated			
	Board of Health			Prohibit injection of wastes other than salt water			
Missouri	Water Pollution Board	Y	Y	Y	-	-	Y
Montana	Oil and Gas Conservation Commission	Y	Y	-	Y	Y	-
Nebraska	Department of Water Resources	g	-	g	-	-	-
Nevada				Not allowed			
New Hampshire		-	-	-	-	-	-
New Jersey	Department of Conservation	Y	-	-	Y	Y	Y
	Department of Health	-	-	-	-	-	Y
New Mexico	Department of Public Health	Y	Y	Y	-	Y	Y
New York	Department of Health	Y	Y	-	Y	Y	-
North Carolina				No information			
North Dakota	State Geologist	Y	Y	Y	-	-	-
Ohio	Water Pollution Board	Y	Y	Y	-	-	-
Oklahoma	Corporation Commission	Y	Y	Y	-	Y	Y
	Department of Health	Y	Y	Y	-	Y	Y
	Water Resources	Y	Y	Y	-	Y	Y
Oregon	Sanitary Authority	-	Y	-	-	-	-
Pennsylvania	Sanitary Water Board	Y	Y	Y	Y	Y	Y
Puerto Rico	Department of Health	Y	Y	Y	-	Y	-
	Aqueduct and Sewage Authority	-	-	-	-	-	Y
Rhode Island		-	-	-	-	-	-
South Carolina	Water Pollution Control Authority			Not used			
South Dakota		-	-	-	-	-	-
Tennessee				Not permitted			
Texas	Water Commission	Y	Y	Y	-	Y	Y
Utah	Water Pollution Control Board	Y	Y	-	Y	Y	Y
	Oil and Gas Commission	-	-	Y	-	Y	Y
Vermont				Not used			
Virginia	Water Control Board	Y	Y	Y	-	Y	-
Virgin Islands		-	-	-	-	-	-
Washington	Pollution Control Commission (Department of Health if sewage is involved)	Y	Y	Y	-	Y	-
West Virginia	Water Resources Board	Y	Y	Y	-	Y	-
Wisconsin				Not allowed			
Wyoming	Department of Health	-	Y	-	-	-	-

[a] Prohibit disposal of waste into strata bearing water that is used or suitable for use as a domestic water supply.

[b] If waste disposal wells should be used, the Water Pollution Commission requirement that a certificate of approval must be secured for sewers and waste treatment facilities would apply.

[c] Oil field brine only.

[d] Oil and gas wells only.

[e] In some instances.

[f] For certain specific wastes.

[g] Oil and gas field wastes (?).

5 shows that the average total cost of a 1,750-foot oil or gas well is about $17,500. The cost of one 100-horsepower centrifugal pump is $6,500 (Figure 6). The cost of a water-conditioning plant to inject 288,000 gpd (200 gpm), shown in Figure 7, is about $45,000. The total cost of this hypothetical waste injection system is $69,000.

The total cost of the above-listed existing injection well systems ranges from about 60 percent less to 700 percent greater than the $69,000 estimate for a 1,750-foot well, pump, and water-conditioning plant. The $30,000 injection well system listed above includes no water-conditioning equipment. The extreme range in cost in the above-listed existing systems is probably caused by variation in cost of the surface facilities, rather than of the injection wells themselves.

Donaldson *(143)* estimated that the cost to be anticipated for an injection system with a 3,000-foot well under favorable conditions is $200,000. The estimated cost of the surface equipment constitutes $125,000 of this total.

STATE REGULATIONS

The results of a recent questionnaire circulated to each of the 50 states by the Conference of State Sanitary Engineers *(144)* are summarized in Table 3. Agencies in 34 states appear to allow the construction of waste injection wells subject to certain requirements. Two states have regulations that apply only to oilfield brine injection wells; four specify that they do not, by policy, allow the construction of waste injection wells; three replied that waste injection wells are not used; five apparently do not discourage the use of waste injection wells but do not have specific requirements for them; and two supplied no information.

Correspondence with the various states has shown that the results shown in Table 3 can be misleading in some cases, since only one state (Texas) has laws that pertain specifically to deep industrial-waste injection wells. The requirements shown in Table 3 for states other than Texas pertain specifically to oilfield brine injection wells or to waste disposal systems in general.

In addition to the four states that indicated that deep-well waste injection is not allowed, Minnesota presently allows only the injection of potable water, and Chio and Mississippi allow only the injection of oilfield brines. Many other states (for example, Delaware, Florida, Idaho, Oregon) do not completely rule out the use of deep injection wells, but because of geologic considerations, as discussed in an earlier section of this paper, suitable sites for injection wells are not available or are extremely restricted.

RESEARCH NEEDS

The technology of locating, drilling, testing, completing, and utilizing deep wells has been developed by the petroleum industry. This knowledge, especially in the area of brine injection and water flooding for secondary recovery of oil, is applicable to the problem of the injection of industrial wastes. Certain problems pertaining to the injection of industrial wastes have not, however, been adequately considered.

General Geologic Considerations

To the knowledge of the writer, the locations of existing waste injection wells have not been selected with the objective of confining injected waste laterally within a specified geologic structure or within some specified radius of an injection well. Such a procedure may not always be practical, but, under some circumstances, it may be desirable to store waste in a predetermined manner rather than allow it to circulate randomly into the disposal horizon. This procedure would be advantageous, since it would allow a rather precise knowledge of the underground location of injected waste and would, perhaps, permit its recovery if so desired.

To restrict the lateral spread of injected waste, without use of artificial hydrologic boundaries, methods would have to be developed for predicting the rate of mixing of injected waste with interstitial waters and the rate of diffusion of waste away from the center of injection under various hydrologic conditions.

A specific problem of this type is the safe location of injection wells near the margins of synclinal basins and in coastal-plain areas. In these cases, strata contain fresh water near the outcrop, and salt water and commercial hydrocarbon accumulations at depth down the dip of the seaward-inclined strata. To select the safe location of injection wells with respect to fresh water and oil and gas wells, equations to predict rate and direction of dispersion of injected waste under hydrodynamic conditions would have to be developed and tested.

Areas Geologically Suitable for Deep-Well Injection of Waste

As has been discussed, studies of some major synclinal basins and the Atlantic and Gulf Coastal Plains have been carried out to define their general suitability for the injection of radioactive waste. These studies are also useful for defining the suitability of these areas for the disposal of other industrial wastes.

Elimination of certain areas as potential sites for the injection of industrial waste is possible from the most general geologic considerations. After outlining the synclinal basins and areas generally unsuitable

for deep-well waste injection large areas remain (Figure 1) that have not been evaluated in regard to their general suitability for the deep-well injection of industrial waste. Such an evaluation can, in many cases, be made from existing geologic literature.

Evaluation of the Disposal Horizon

SAFE INJECTION PRESSURE

As fluid is injected into saturated porous media, the injection pressure can be shown to increase with time. Petroleum industry experience with water injection wells has shown that, at some critical input pressure, an abrupt increase in the water acceptance per unit of pressure occurs. At present consideration of this critical input pressure as the limiting safe injection pressure seems prudent, since the increased intake rate may result from hydraulic fracturing that could conceivably damage the confining strata. It is not, however, certain that hydraulic fractures, if they do occur, are vertical or that they damage the confining beds if they are vertical.

Research is needed to determine the influence, if any, of hydraulic fracturing on confining beds and establish a means of safely determining or predicting the maximum safe injection pressure. This is an important problem since the useful life of an injection well may be controlled by the maximum safe injection pressure, and deliberate hydraulic fracturing has been suggested as a means of increasing the intake rate of injection wells.

ESTIMATION OF THE RATE OF PRESSURE INCREASE IN AN INJECTION WELL

Koenig *(38)* concluded, after reviewing the cost of injection well construction, that theoretical and practical study is required to predict the pressure behavior of waste injection wells to assure that rapid pressure buildup will not make the system uneconomical.

Equations have been developed that permit computation of the rate of pressure increase in an injection well under various specified boundary conditions. The existing solutions should be reviewed and new solutions developed if necessary. An interesting project would be to field test various flow equations on several new injection wells and compare the predicted results with actual performance.

PUMPING AND INJECTION TESTS

Pumping and injection tests are performed by petroleum engineers and ground-water hydrologists to determine the gross, in-place physical properties of buried strata. Available testing methods should be re-

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viewed and new methods developed, if necessary, since these tests are probably the best means of determining the engineering properties of an injection horizon during and immediately after the drilling of a well.

COMPATIBILITY OF INJECTED AND INTERSTITIAL FLUIDS AND MINERALS

The necessity of treating water before injection to prevent plugging at the injection face or swelling of clay minerals is well recognized, but how importantly reactions within the injection horizon between interstitial and injected waters can influence permeability is not certain.

Research should be undertaken to define the importance of reactions between interstitial and injected waters and establish reliable criteria for predicting and testing the compatibility of formation waters and injected waters. It should be possible to examine the properties of the more important types of industrial wastes and formulate some helpful general criteria regarding the compatibility of these wastes with interstitial waters.

Determination of Wastes Suitable for Deep-Well Injection

The Subcommittee on Waste Disposal of the Committee on Sanitary Engineering and Environment, National Academy of Sciences-National Research Council (Committee reports June 25, 1962, and January 20, 1964) has stated that, since the injection of liquid wastes into a subsurface rock formation constitutes the utilization of limited useful space, injection wells cannot be considered for any quantity and type of waste. In addition, some wastes are not physically and chemically suitable for deep-well injection.

Research is needed to define those wastes that, based on the above considerations, are suitable for deep-well injection. It may be possible to categorize certain common types of highly toxic and relatively untreatable wastes and to generalize about the preparation, if any, that these wastes may need to make them suitable for deep-well injection. Such a study, in combination with previously suggested geologic studies and economic and legal considerations, is necessary to allow industries and pollution control agencies to assess rapidly the feasibility of deep-well injection as a solution to some specific waste disposal and pollution control problems.

A concept not yet investigated is the possibility of constructing injection wells to serve an industrial complex such as exists in many urban centers. The well or wells could be constructed jointly by the various industries involved or by an independent organization that could charge for well use. Evaluating the practicability of such a program based on existing knowledge and knowledge that could be

developed in previously suggested research efforts should be possible. The economics of community injection wells could be very favorable; these wells could significantly reduce the pollution of surface waters with toxic industrial wastes.

Data Concerning Existing Waste-Injection Wells

To take best advantage of existing knowledge concerning deep-well injection of waste, a compilation of data on the design and performance of existing wells is needed. A national registry for deep waste injection wells was suggested by the National Subcommittee on Waste Disposal of the Committee on Sanitary Engineering, National Academy of Sciences-National Research Council in their meeting of January 8, 1964. Such a registry would, if the proper data were obtained, be useful for research purposes. The following tabulation outlines the minimum information the writer feels should be obtained for each existing or new well.

SUGGESTED MINIMUM INFORMATION TO BE INCLUDED IN A DEEP-WASTE-INJECTION WELL REGISTRY

1. Operator of well and organizations using well
2. Location of well
3. Date of initiation of operation
4. A. Depth of well
   B. Depths of injection horizons
   C. Names of geologic formations used for injection, including formations for future development.
5. A. Chemical and physical character of wastes to be injected
   B. Chemical character of formation fluids
6. Treatment applied to waste prior to injection
7. Injection rate
8. Injection pressure

Recommendations for Legal Requirements Pertaining to Waste-Injection Well Permitting, Construction, and Evaluation

Examination of the laws of the various states concerning deep-well injection, and correspondence with the various state agencies concerned

with deep-well waste injection have indicated a need for the establishment of recommendations pertaining to the practice of waste injection into deep wells. These recommendations could serve as a basis for legal requirements in states where the present laws are not adequate or as a guide in states where laws are broad and do not include specific requirements.

CONCLUSIONS

Based on existing knowledge and experience, the deep-well injection of liquid wastes is thought to be technically feasible in many areas of the country and, if properly planned and implemented, is not likely to be harmful to natural resources. Nevertheless, because the space available for fluid injection is limited, only concentrated toxic wastes that cannot otherwise be satisfactorily disposed should be considered for deep-well injection.

Most of the technical knowledge and experience necessary to carry out the deep-well injection of liquid wastes is now available, but some problems peculiar to the injection of industrial wastes seem worthy of investigation.

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